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Availability modeling and optimization of dynamic multi-state series–parallel systems with random reconfiguration

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ABSTRACT

Most studies on multi-state series–parallel systems focus on the static type of system architecture. However, it is insufficient to model many complex industrial systems having several operation phases and each requires a subset of the subsystems combined together to perform certain tasks. To bridge this gap, this study takes into account this type of dynamic behavior in the multi-state series–parallel system and proposes an analytical approach to calculate the system availability and the operation cost. In this approach, Markov process is used to model the dynamics of system phase changing and component state changing, Markov reward model is used to calculate the operation cost associated with the dynamics, and universal generating function (UGF) is used to build system availability function from the system phase model and the component models. Based upon these models, an optimization problem is formulated to minimize the total system cost with the constraint that system availability is greater than a desired level. The genetic algorithm is then applied to solve the optimization problem. The proposed modeling and solution procedures are illustrated on a system design problem modified from a real-world maritime oil transportation system.

1. Introduction

The multi-state series–parallel system (MSSPS) is among the most popular multi-state systems (MSS) being studied [21,16,33,1,38]. The typical architecture of a MSSPS consists of N subsystems connected in series, and in each subsystem s_i there are n_i components connected in parallel (see Fig. 1). Based on this general structure, most existing studies on MSSPS optimization intend to optimize the types and the numbers of the components in each subsystem [10,12]. One key assumption of these studies is that the system topology remains unchanged throughout the entire system life time.

Levitin et al. [22] proposed a recursive method for the exact reliability evaluation of phased-mission systems consisting of non-identical independent nonrepairable multistate elements. A structure optimization problem was also studied for a binary system working in multiple phases [3]. Though phased-mission systems can have different structures in different phase, the duration for each phase is constant. In practice, a number of complex industrial systems, such as oil transportation systems [35], shipping systems [14], and railway transportation systems [43] have several operation phases with random duration, at each only a fraction of the subsystems are operating to perform certain task. For instance, Soszynska [35] described a real-world oil transportation system with three pipeline subsystems connected in series to perform five tasks; each involves at most three subsystems at operation. Fig. 2 depicts a few 'snapshots' of the operational phases of a MSSPS, where an operation phase b is associated with a certain probability representing the likelihood that the system remains at phase b throughout its life time. It is seen that the stable structure in Fig. 1 can be regarded as a special case (i.e. with all subsystems functioning at all time) of the dynamic structure implied by Fig. 2.

At the component level, it is well known that the multi-state components also exhibit dynamic behaviors. For example, the multi-state components are often subject to aging process [12,28] and maintenance activities [44]. These situations indicate that component state probability is not always a constant throughout time.

Moreover, the costs associated with the dynamics (both at system level and component level) should also be considered in the optimization problem. To the best of our knowledge, most existing studies in this field compute the total system cost by taking into account only the capital cost of the component, which is the one-time expense to construct or purchase such component. In practice, the operation cost is incurred by almost every type of equipment (e.g. railways [42], telecommunication devices [13], etc)—unless the equipment has no power/energy consumption, does not deteriorate and thus requires no maintenance.

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Acronyms

CDF	cumulative distribution function
DMSSPS	dynamic multi-state series–parallel system
GA	genetic algorithm
MP	Markov process
MRM	Markov reward model
MSS	multi-state system
MSSPS	multi-state series–parallel system
PMF	probability mass function
ROP	redundancy optimization problem
UGF	universal generating function

Notations

N	total number of subsystems connected in series
s_i	the set of components in the i-th subsystem
O	total number of operation phases for MSS
Z_b	the set of the indexes of the subsystems involved in operation phase b
S_b	the set of subsystems involved in operation phase b
G_b	system performance level at operation phase b
W_b	system demand at operation phase b
$\boldsymbol{S}$	the set of all subsystems
n_i	total number of components in subsystem i
$\boldsymbol{E}_j$	transition rate matrix of component j
$\mathfrak{R}_j$	reward matrix of component j
$p_k^j(t)$	probability of component j at state k at time t
$\boldsymbol{p}_j(t)$	time dependent state probability vector of component j
$v_k^j(t)$	expected total reward of component j at time t with initial state at k
$\boldsymbol{v_j}(t)$	the time dependent reward vector of component j
g_k^j	performance level of component j at state k
$u_j(z)=\sum_{k=0}^{M_j} p_k^j(t) z^{g_k^j}$	the u-function representing the performance distribution of component j
M_j	the highest state of component j
$u_i(z)$	the u-function representing the performance distribution of subsystem i
$u_b(z)$	the u-function representing the whole system's the performance distribution during phase b
$\boldsymbol{g}_j$	performance vector of component j
G_j	random performance rate of component j
$\varphi_S(\bullet)$	system structure function
$\otimes_\varphi$	the UGF operator
$\boldsymbol{F}_s$	transition rate matrix of system level dynamics
$p_b(t)$	transient probability of system staying at operation phase b
$A_S(t)$	system availability
B_i	total number of component types available for subsystem i
U_i	maximum allowable number of components in subsystem i
x_{ij}	number of type j components in subsystem i
X	system design vector $(x_{11}, x_{12}, \ldots, x_{1B_1}; \ldots; x_{N1}, x_{N2}, \ldots, x_{NB_N})$

To address the issues above, we propose an analytic approach that combines Markov process to model the dynamics at both system and component levels, the universal generating function (UGF) to derive [39] the system availability function, and the Markov reward model to compute the operation costs associated with system dynamics. Based on this approach, an optimization problem is formulated with the consideration of the availability of the system and its operation costs. Though there are different approaches, such as Pareto dominance [36,34,25] and weighted sum [7] to deal with multi-objective optimization problems, an usual way is to optimize one objective constrained by the other ones [5,23,30–32,41]. In particular, this paper aims to minimize the total system cost with the constraint that system availability is greater than a predetermined level. In order to solve the optimization problem which is combinatorial in nature, a genetic algorithm (GA) technique is adopted. The rest of this paper is organized as follows: Section 2 develops the general model of the dynamic multi-state series–parallel system (DMSSPS), derives the system availability function and the system operation cost function. Section 3 presents the optimization problem and the solution technique. Section 4 presents a numeric example on oil transportation system design. Section 5 concludes this study and points out directions for future extensions.

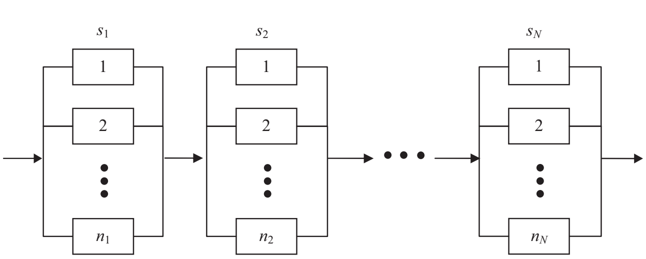

Fig. 1. The classical structure of a multi-state series–parallel system.

2. General model of dynamic multi-state series–parallel system

The assumptions of the DMSSPS are presented as follows:

- All components are statistically independent from each other. This assumption appears in most previous multi-state reliability/availability studies [16,17,36].

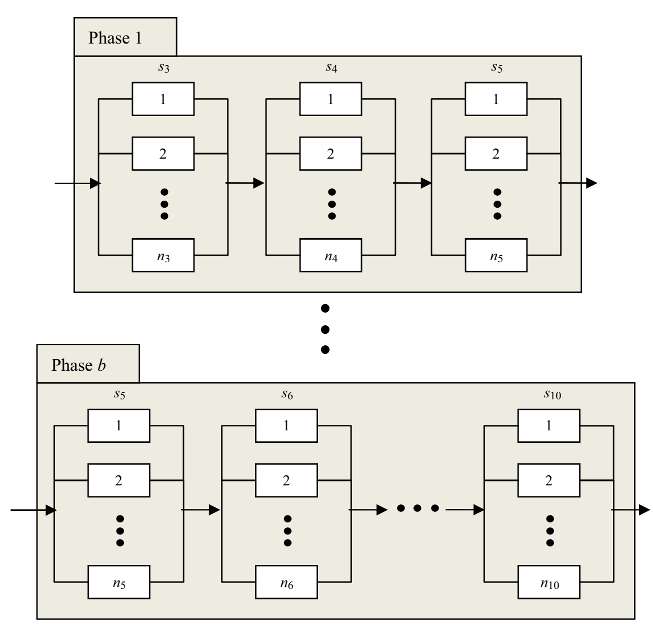

Fig. 2. Different operation phases of a MSSPS.